Polarized-boson pairs at NLO in the SMEFT

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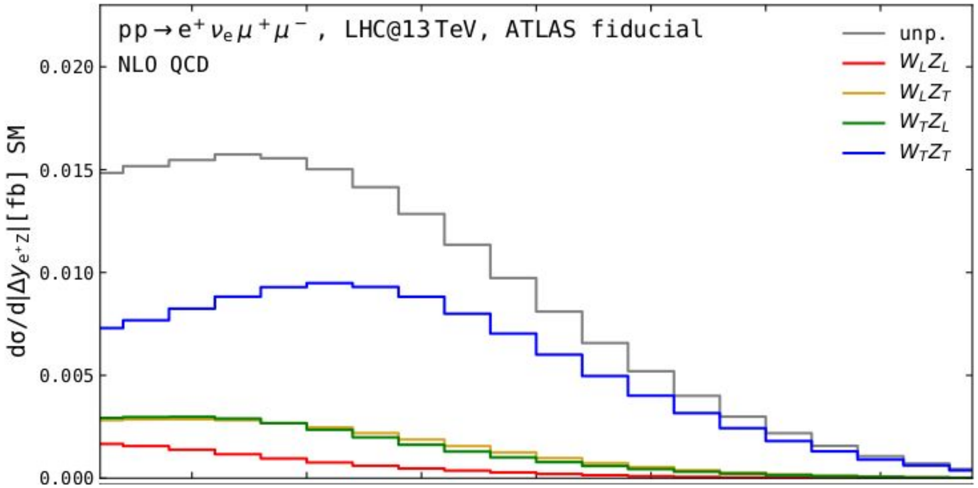
Outline

- Introduction & motivation
- SMEFT
- Polarized states: definition and computation details
- Results

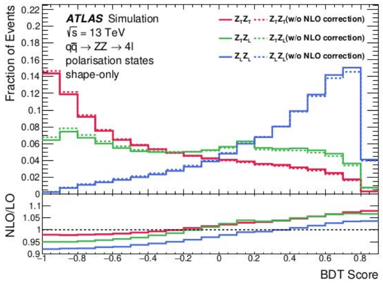


Work done in collaboration with: U. Haisch, J. Linder, G. Pelliccioli, G. Zanderighi. [2507.21768]
Some results from A. Iavarone MSc thesis.
Figures credit: J. Lindert (+ A. Iavarone)

Why polarized bosons?

- EW symmetry breaking: goldstone bosons ⟵⟶ longitudinal polarisations
- Studying polarisations → studying EWSB at its core
- Hopefully, this way one could also increase sensitivity to New Physics effects
- This talk: SMEFT approach, and focus on diboson production
- Not possible to measure polarisations directly → typically, template fitting for polarized VV production
- Our results: (hopefully) optimal tool, including NLO+PS corrections, improving current status

  - ATLAS ‘23:
  3-step reweighting: (polarisation, interf. effects,
  residual higher order effects)



SMEFT

- Model independent New Physics; can be improved systematically
- This work: Warsaw basis [Grzadkowski et.al '10]

$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{C_i(\mu)}{\Lambda^2} Q_i$$

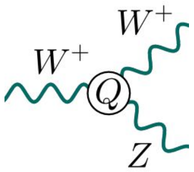
$$Q_{HB} = H^\dagger H\, B_{\mu\nu} B^{\mu\nu}\,, \qquad Q_{H\widetilde{B}} = H^\dagger H\, B_{\mu\nu} \widetilde{B}^{\mu\nu}\,,$$

$$Q_{HW} = H^\dagger H\, W^i_{\mu\nu} W^{i,\mu\nu}\,, \qquad Q_{H\widetilde{W}} = H^\dagger H\, W^i_{\mu\nu} \widetilde{W}^{i,\mu\nu}\,,$$

$$Q_{HWB} = H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}\,, \qquad Q_{H\widetilde{W}B} = H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}\,,$$

$$Q_W = \epsilon_{ijk} W^{i,\nu}_{\mu} W^{j,\lambda}_{\nu} W^{k,\mu}_{\lambda}\,, \qquad Q_{\widetilde{W}} = \epsilon_{ijk} W^{i,\nu}_{\mu} W^{j,\lambda}_{\nu} \widetilde{W}^{k,\mu}_{\lambda}\,.$$

- Pheno: focus on operators changing diboson production (TGC)

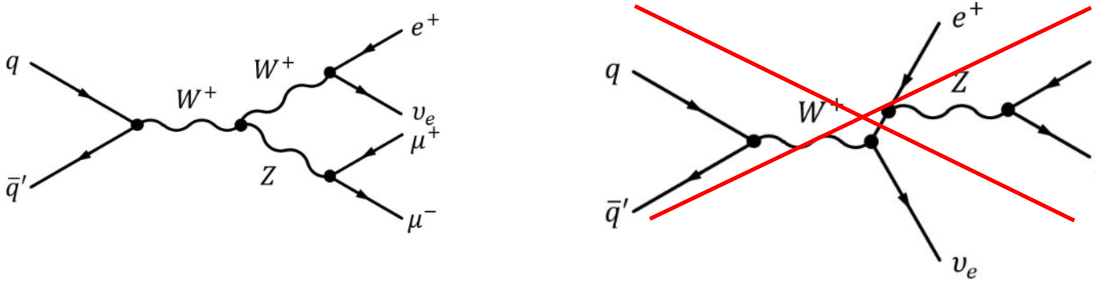


- $\mathcal{A}_{\text{SMEFT}} = \mathcal{A}_{\text{SM}} + \mathcal{A}_{d=6}$ $\qquad d\sigma = d\sigma_{\text{SM}} + d\sigma_{lin} + d\sigma_{quad}$

Polarized bosons: (double) pole approximation

- Polarized boson: strictly speaking on mass shell

- Discard non resonant diagrams



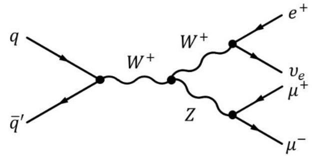
- To retain gauge invariance: - narrow width approximation
  - (Double) pole approximation [Denner et al. hepph: 0006307]

⇒ DPA: in evaluating numerator of amplitudes, map final state momenta such that they are on shell:

$$(p_e + p_\nu)^2 \rightarrow (\tilde{p}_e + \tilde{p}_\nu)^2 = m_W^2$$
$$(p_{\mu^+} + p_{\mu^-})^2 \rightarrow (\tilde{p}_{\mu^+} + \tilde{p}_{\mu^-})^2 = m_Z^2$$

Polarized bosons: cross sections

- Polarized bosons: apply projection to the resonant diagrams



- Production + decay of polarized bosons [Ballestrero ‘17, Denner,Pellicciol ‘20]

$$\mathcal{A}^{\text{unpol}} = \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - m^2 + im\Gamma} \mathcal{D}_\nu$$
$$= \mathcal{P}_\mu \frac{\sum_\lambda \epsilon^\mu_\lambda(k)\epsilon^{*\nu}_\lambda(k)}{k^2 - m^2 + im\Gamma} \mathcal{D}_\nu$$

$$\mathcal{A}_\lambda \equiv \mathcal{P}_\mu \frac{\epsilon^\mu_\lambda(k)\epsilon^{*\nu}_\lambda(k)}{k^2 - m^2 + im\Gamma} \mathcal{D}_\nu$$

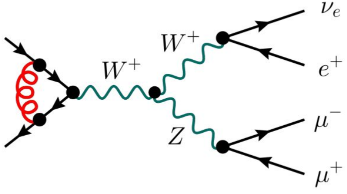
- Polarized cross section:

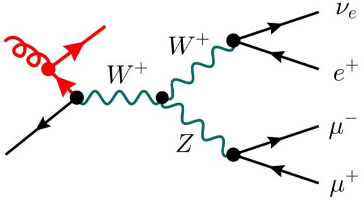
$$|\mathcal{A}^{\text{unpol}}|^2 = \boxed{\sum_\lambda |\mathcal{A}_\lambda|^2} + \sum_{\lambda \neq \lambda'} (\mathcal{A}^*_\lambda \mathcal{A}_{\lambda'})$$

- Generalization to multiple bosons possible (here 2)
- Polarization states: not Lorentz invariant → defined in VV rest frame
- Amplitudes from `Recola 2` [Denner et al. 1705.06053, Denner et al. 1711.07388]

NLO corrections

- NLO (QCD): $$\bar{B}(\Phi_4) = B(\bar{\Phi}_4) + V_{\rm reg}(\bar{\Phi}_4) + \int d\Phi_{\rm rad}\, \left[R(\bar{\Phi}_4, \Phi_{\rm rad}) - C(\bar{\Phi}_4, \Phi_{\rm rad})\right]$$





- IR singularities subtracted through FKS scheme
  - DPA procedure → affects production (sub)amplitudes
  - need local cancellation of real and counterterms → first FKS map, then DPA one

$$\Phi_4 = \{x_1, x_2; k_1, \ldots, k_4\} \xrightarrow{\text{FKS}} \{\bar{\Phi}_4, \Phi_{\rm rad}\} = \{\bar{x}_1, \bar{x}_2; \bar{k}_1, \ldots, \bar{k}_4, k_{\rm rad}\}$$

$$\xrightarrow{\text{DPA}} \{\tilde{\bar{\Phi}}_4, \Phi_{\rm rad}\} = \{\bar{x}_1, \bar{x}_2; \tilde{\bar{k}}_1, \ldots, \tilde{\bar{k}}_4, k_{\rm rad}\}$$

$$\bar{B}(\tilde{\Phi}_4) = B(\tilde{\Phi}_4) + V_{\rm reg}(\tilde{\Phi}_4) + \int d\Phi_{\rm rad}\, \left[R(\tilde{\bar{\Phi}}_4, \Phi_{\rm rad}) - C(\tilde{\bar{\Phi}}_4, \Phi_{\rm rad})\right]$$

- Much of the above built from code developed in SM NLO+PS polarized diboson production [Pelliccioli,Zanderighi ‘23] (also partially built starting from [Chiesa et al. ‘20])

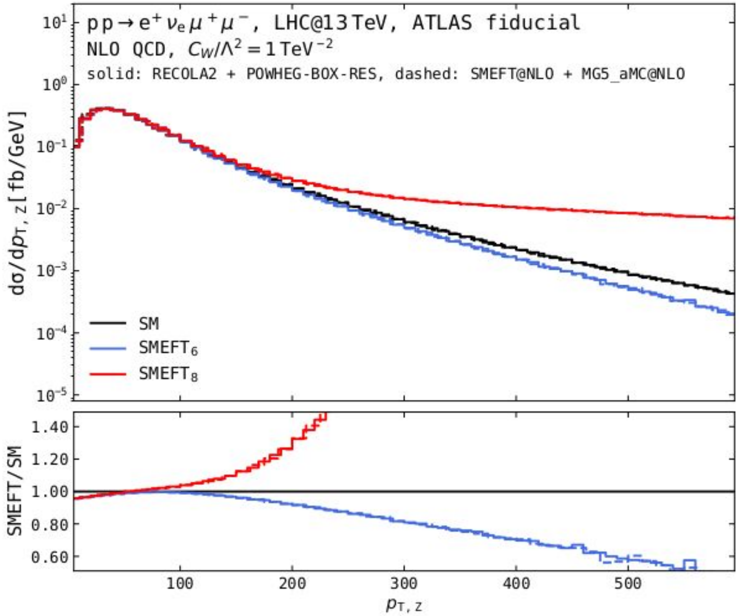
NLO corrections (validation)

- NLO (SMEFT) results validated against SMEFT@NLO+MG5_aMC@NLO [Faham et al. '24]

$$Q_W = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} W_\lambda^{k,\mu}\,, \qquad Q_{\widetilde{W}} = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} \widetilde{W}_\lambda^{k,\mu}$$

contribution	this work	MadGraph
SM	35.30(3) fb	35.35(1) fb
Q_W (lin.)	−0.996(3) fb	−0.997(2) fb
Q_W (quad.)	6.57(1) fb	6.58(1) fb
$Q_{\widetilde{W}}$ (lin.)	−0.062(2) fb	−0.059(1) fb
$Q_{\widetilde{W}}$ (quad.)	6.72(1) fb	6.71(1) fb

ATLAS cuts, c_{WWW}=1 TeV^{-2}

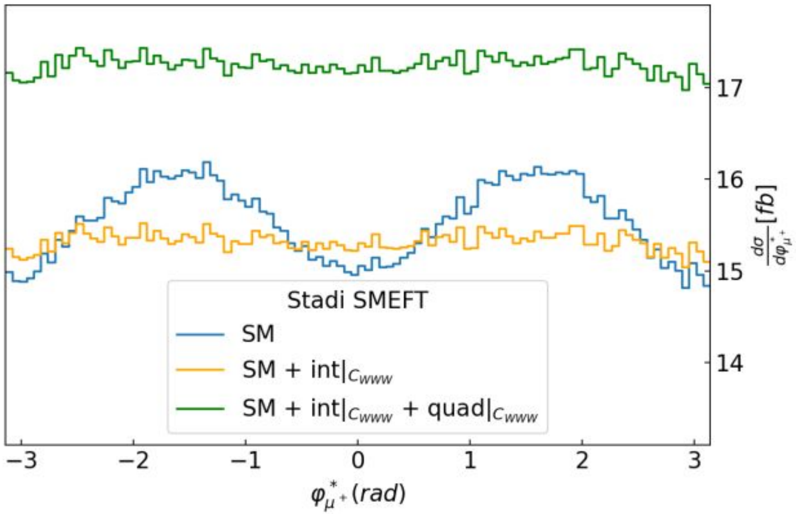


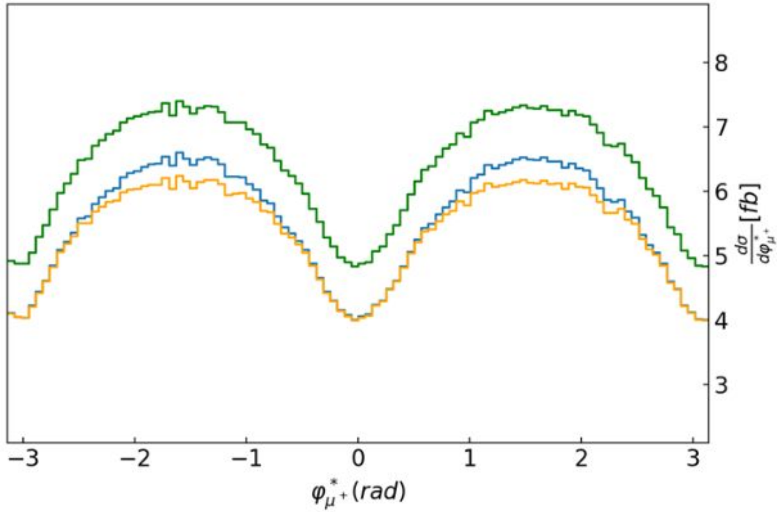
- Full agreement

NLO corrections (inclusive vs fiducial)

- Plots from A. Iavarone MSc thesis

$$Q_W = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} W_\lambda^{k,\mu}\,, \qquad Q_{\widetilde{W}} = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} \widetilde{W}_\lambda^{k,\mu}$$



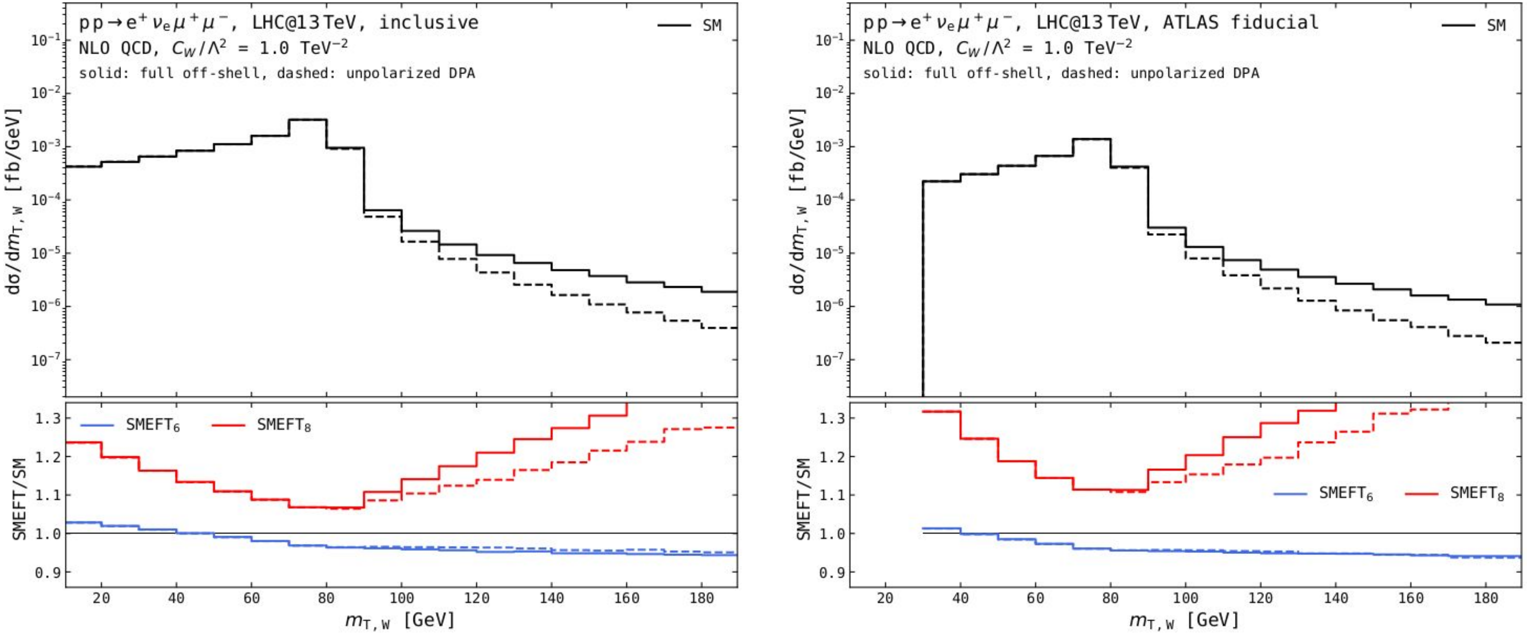


- Inclusive vs ATLAS cuts, c_{www}=1 TeV^{-2}

[1] ATLAS collaboration. Physics LettersB, 843:137895,
[2] ATLAS collaboration. Eur.Phys. J. C, 79(6):535, 2019

DPA vs full result

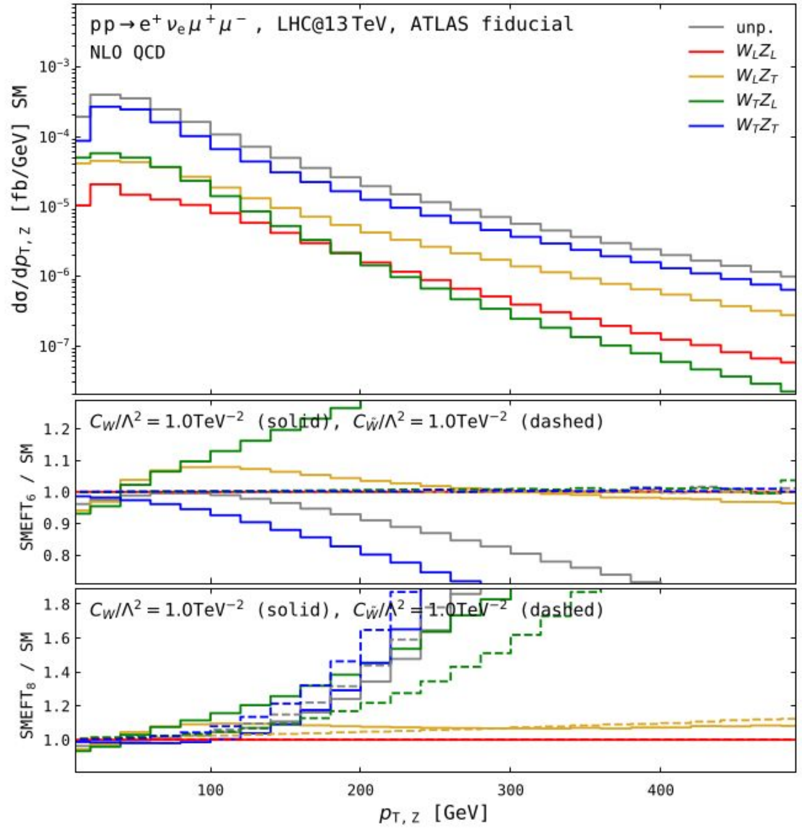
$$m_{T,W} = \sqrt{2 p_{T,e} p_{T,\text{miss}} \left(1 - \cos \Delta\phi_{e\text{miss}}\right)}$$



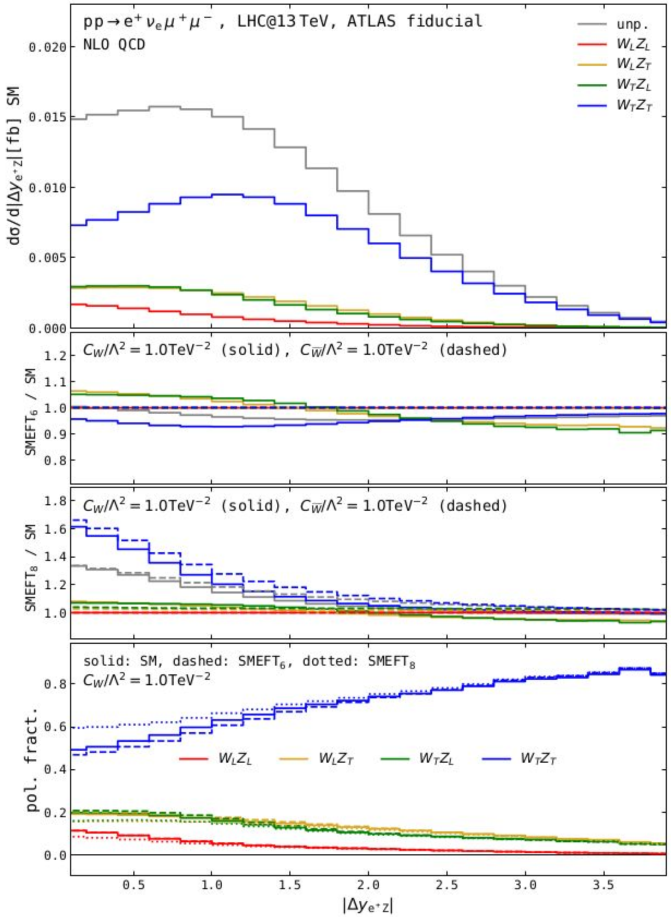
- Below threshold: DPA ~ full off-shell
- Above threshold: DPA deviates (hel. supp→ SMEFT6~SM;

main effect: no WWγ contrib in DPA, visible in SMEFT8).

SMEFT polarised results



[plot from J. Linder]

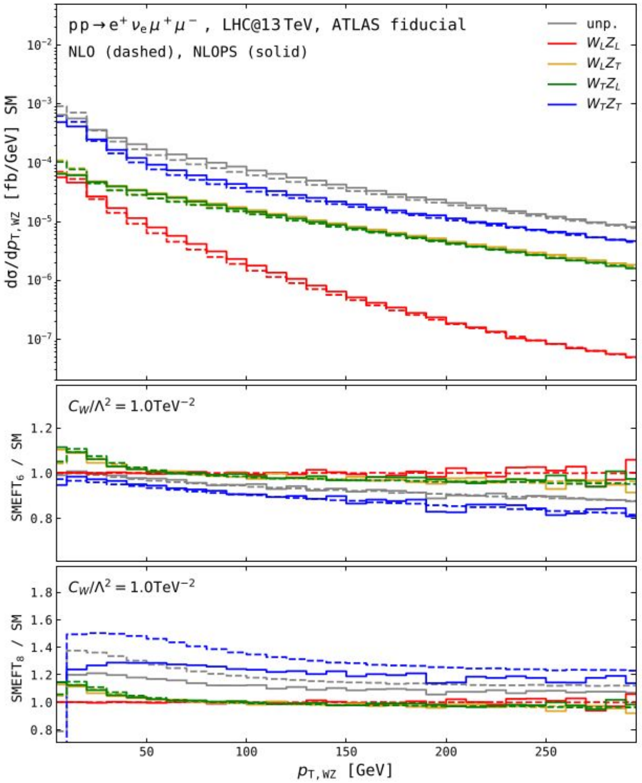


→ LL SMEFT amplitude (single insertion of Q_W / Q_{Wtilde} operator) vanishes

ΔY correlated with Z-W scattering angle

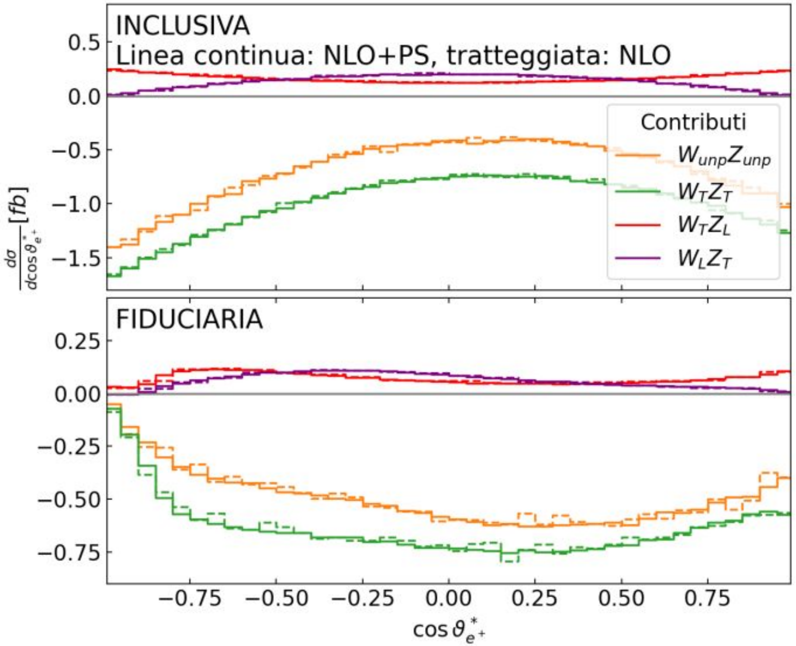
NLO+PS polarized results

- POWHEG modified also in Sudakov part (FKS → DPA) (as for real part)



[plot from J. Linder]

$$d\sigma_{SMEFT} = d\sigma_{SM} + \boldsymbol{d\sigma_{lin}} + d\sigma_{quad}$$



[plot from A. Iavarone]

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\vartheta^*} = \frac{3}{8}\left[2f_L \sin^2\vartheta^* + f_+\left(1+\cos^2\vartheta^* + 2c_{LR}\cos\vartheta^*\right) + f_-\left(1+\cos^2\vartheta^* - 2c_{LR}\cos\vartheta^*\right)\right]$$

Conclusions

- Presented a computation at NLO(+PS) QCD for polarized diboson production, including SMEFT effects

- Fully differential polarization fractions

- Besides allowing for a more solid understanding of kinematic effects, hopefully such results will also be used for EXP searches (e.g. template fitting, or other methods)

- Code available within POWHEG BOX RES (now in gitlab): https://gitlab.com/POWHEG-BOX/RES/User-Processes/VV_pol

Thank you for your attention!